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Composite residuosity and its application to cryptography

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Abstract It is well-known that a quadratic residue is adopted to public key cryptosystem, for example, we show Rabin cryptosystem. In this paper, we describe a composite residue and its application to cryptography.

1. Introduction

At first, we review a quadratic residue and its application to cryptography. Suppose p is an odd prime and a is an integer. a is defined to be a quadratic residue modulo p if $a \not\equiv 0 \pmod{p}$ and the congruence $y^2 \equiv a \pmod{p}$ has a solution y where nonnegative y is less than n. It is well-known that a quadratic residue is adopted to public key cryptosystems. For example, we show Rabin Cryptosystem [5]. Let $n = pq$, where p and q are primes, and $p, q \equiv 3 \pmod{4}$. The value n is the public key, while p and q are the private key. For a plaintext $m < n$, we define the cipertext $c = m^2 \pmod{n}$. Quadratic residue is adopted in a trapdoor mechanism of this public key cryptosystem. As well, the public key cryptosystem by Kurosawa et. al. [2] also utilized a quadratic residue. Moreover, the public key cryptosystem by Naccache and Stern [3] utilized a higher residue. Further, the public key cryptosystem by Paillier [4] utilized a composite residue. In this paper, we describe a composite residue and its application to cryptography.

2. Composite residue

In this section, we describe a definition of a composite residue. A composite residue, that is, an n-th residue is introduced by Benaloh [1].

We set $n = pq$ where p and q are large primes. In this case, we denote by $\phi(n) = (p-1)(q-1)$ the Euler's function. And we denote by $\lambda(n) = \mathrm{lcm}(p-1, q-1)$ the least common multiple of $p-1$ and $q-1$. We adopt λ instead of $\lambda(n)$ for visual comfort.

We denote by Z_{n^2} a residue class ring modulo n^2. And We denote by $Z^*_{n^2}$ its invertible element set. The set $Z^*_{n^2}$ is a multiplicative subgroup of Z_{n^2} of order $\phi(n^2) = n\phi(n) = pq(p-1)(q-1)$.

For any $w \in Z^*_{n^2}$, the following equations hold,

$$w^{\lambda} = 1 \pmod{n},$$

$$w^{n\lambda} = 1 \pmod{n^2}.$$

Definition 2.1 . *A number z is said to be an n-th residue modulo n^2 if there exists a number $y \in Z^*_{n^2}$, such that*

$$z = y^n \pmod{n^2}.$$

For example, we suppose $p = 3$, $q = 5$, that is, $n = 15$. Then we obtain $\phi(n) = 8$, $\lambda = 4$, $\phi(n^2) = 120$, and that every element of the set $\{1, 26, 82, 107, 118, 143, 199, 224\}$ an n-th residue modulo n^2.

3. Property of Composite residue

In this section, we describe some properties of an n-th residue. We set $n = pq$ where p and q are large primes.

The set of n-th residues is a multiplicative subgroup of $Z^*_{n^2}$ of order $\phi(n)$. The problem of deciding n-th residuosity, that is, distinguishing n-th residues from non n-th residues will be denoted by CR[n]. As for prime residuosity, deciding n-th residuosity, is believed to be computationally hard.

Let g be some element of $Z^*_{n^2}$ and denote by ε_g the integer-valued function defined by

$$\begin{array}{ccc} Z_n \times Z^*_n & \rightarrow & Z^*_{n^2} \\ (x, y) & \longmapsto & g^x y^n \pmod{n^2}. \end{array}$$

Here, depending on g, ε_g may feature an interesting property such as the following lemma.

Lemma 3.1 . *If the order of g is a nonzero multiple of n then ε_g is bijection.*

We denote by $\mathcal{B}_\alpha \subset Z^*_{n^2}$ the set of elements of order $n\alpha$ and by $\mathcal{B}$ their disjoint union for $\alpha = 1, \cdots, \lambda$.

In the case of $n = 15$, we obtain the following sets as $\mathcal{B}_\alpha$ and $\mathcal{B}$;

$\mathcal{B}_1 = \{16, 31, 46, 61, 76, 91, 106, 121, 136, 151, 166, 181, 196, 211\}$,
$\mathcal{B}_2 = \{14, 29, 44, 59, 74, 89, 104, 119, 134, 149, 164, 179, 194, 209\}$,
$\mathcal{B}_4 = \{2, 4, 7, 8, 11, 13, 17, 19, 22, 23, 26, 28, 32, 34, 37, 38, 41, 43, 47, 49, 52, 53, 56, 58, 62, 64, 67, 68, 71, 73, 77, 79, 82, 83, 86, 88, 92, 94, 97, 98, 101, 103, 107, 109, 112, 113, 116, 118, 122, 124, 127, 128, 131, 133, 137, 139, 142, 143, 146, 148, 152, 154, 157, 158, 161, 163, 167, 169, 172, 173, 176, 178, 182, 184, 187, 188, 191, 193, 197, 199, 202, 203, 206, 208, 212, 214, 217, 218, 221, 223\}$,
$\mathcal{B} = \mathcal{B}_1 \cup \mathcal{B}_2 \cup \mathcal{B}_4$.

Here, we verify that $\mathcal{B}_i \cap \mathcal{B}_j = \phi$ for $i, j (i \neq j)$.

Definition 3.2 . *Assume that $g \in \mathcal{B}$. For $w \in Z^*_{n^2}$, we call n-th residuosity class of w with respect to g the unique integer $x \in Z_n$ for which there exists $y \in Z^*_n$, such that*

$$\varepsilon_g(x, y) = w.$$

Adopting Benaloh's notations [1], the class of w is denoted $[[w]]_g$. It is worthwhile noticing the following property.

Lemma 3.2 . $[[w]]_g = 0$ *if and only if w is an n-th residue modulo n^2. Furthermore,*

$$\forall w_1, w_2 \in Z^*_{n^2} \qquad [[w_1 w_2]]_g = [[w_1]]_g + [[w_2]]_g \pmod n$$

that is, the class function $w \longmapsto [[w]]_g$ is a homomorphism from $(Z^*_{n^2}, \times)$ to $(Z_n, +)$ for any $g \in \mathcal{B}$.

By Lemma 3.2, it can easily be shown that, for any $w \in Z^*_{n^2}$ and $g_1, g_2 \in \mathcal{B}$, we have

$$[[w]]_{g_1} = [[w]]_{g_2} [[g_2]]_{g_1} \pmod n, \tag{3.1}$$

which yields $[[g_1]]_{g_2} = [[g_2]]_{g_1}{}^{-1} \bmod n$ and thus $[[g_2]]_{g_1}$ is invertible modulo n.

The set

$$S_n = \{u < n^2 \mid u = 1 \pmod n\}$$

is a multiplicative subgroup of integers modulo n^2 over which the function L such that

$$\forall u \in S_n \qquad L(u) = \frac{u-1}{n}$$

is clearly well-defined.

Lemma 3.3 . *For any $w \in Z_{n^2}^*$, there holds as follows,*

$$L(w^\lambda \pmod{n^2}) = \lambda[[w]]_{1+n} \pmod{n}.$$

By Lemma 3.3, for any $g \in \mathcal{B}$ and $w \in Z_{n^2}^*$, we can compute

$$\frac{L(w^\lambda \pmod{n^2})}{L(g^\lambda \pmod{n^2})} = \frac{\lambda[[w]]_{1+n}}{\lambda[[g]]_{1+n}} = \frac{[[w]]_{1+n}}{[[g]]_{1+n}} \pmod{n}.$$

By virtue of Equation 3.1, for any $g \in \mathcal{B}$ and $w \in Z_{n^2}^*$, we can compute

$$\frac{[[w]]_{1+n}}{[[g]]_{1+n}} = [[w]]_g \pmod{n}.$$

Therefore, for any $g \in \mathcal{B}$ and $w \in Z_{n^2}^*$, we can compute

$$\frac{L(w^\lambda \pmod{n^2})}{L(g^\lambda \pmod{n^2})} = [[w]]_g \pmod{n}. \tag{3.2}$$

4. Application to cryptography

Now, we describe the public key cryptosystem based on the n-th residuosity class problem.

Set $n = pq$ and randomly select a base $g \in \mathcal{B}$. We review that ε_g be the function defined by

$$\begin{array}{rcl} Z_n \times Z_n^* & \rightarrow & Z_{n^2}^* \\ (x, y) & \longmapsto & \varepsilon_g(x, y) = g^x y^n \pmod{n^2}. \end{array} \tag{4.1}$$

For the plaintext x, we employ this function ε_g as an encryption function.

Moreover, we review that we define the function L as follows:

$$\begin{array}{rcl} S_n = \{u < n^2 \mid u = 1 \pmod{n}\} & \rightarrow & Z_n \\ u & \longmapsto & L(u) = \frac{u-1}{n}. \end{array} \tag{4.2}$$

For the cipertext $c = \varepsilon_g(x, y)$, we employ the rate of these two functions $L(c^\lambda)$ and $L(g^\lambda)$ as an decryption function.

Theorem 4.1 . *We set $n = pq$ and $\lambda = lcm(p-1, q-1)$. For any $g \in \mathcal{B}$, we obtain public-key cryptosystem as public keys (n, g) and private keys (p, q). For a plaintext $m < n$, we select a random $r < n$, and compute* *the cipertext c by Equation 4.3. For a cipertext $c < n^2$, we compute the plaintext m by Equation 4.4.*

$$c = g^m r^n \pmod{n^2}, \tag{4.3}$$

$$m = \frac{L(c^\lambda \pmod{n^2})}{L(g^\lambda \pmod{n^2})} \pmod{n}. \tag{4.4}$$

For example, we suppose $n = 15$ and $g = 14$. Then, for a plaintext $m = 3$ and a random $r = 4$, we compute the cipertext $c = 206$ by Equation 4.3. For a cipertext $c = 206$, we compute the plaintext

$$m = \frac{L(206^4 \pmod{n^2})}{L(14^4 \pmod{n^2})} = \frac{L(46)}{L(166)} \pmod{n}$$

by Equation 4.4. Here, we compute

$$L(46) = \frac{46-1}{15} = 3 \pmod{n}$$

$$L(166) = \frac{166-1}{15} = 11 \pmod{n}$$

by Equation 4.2. Therefore, we can obtain

$$m = \frac{L(46)}{L(166)} = \frac{3}{11} = 3. \pmod{n}$$

For $n = pq$, we obtain the public key cryptosystem based on the n-th residuosity class problem.

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